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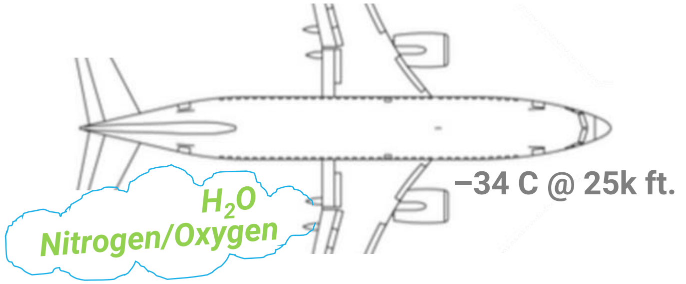
Zero-carbon Ammonia-Powered Turboelectric Propulsion System (ZAPturbo)

Lance Smith, Raytheon Technologies Research Center (RTRC)

Project Vision

- Provide a liquid-fueled, carbon-free, non-cryogenic aircraft propulsion system for future flight.
- Leverage the unique properties of ammonia to achieve ultra-high energy efficiency (66%), to offset the extra weight-per-energy of ammonia.



REEACH / ASCEND Kickoff Meeting
January 26, 27, 28, 2021

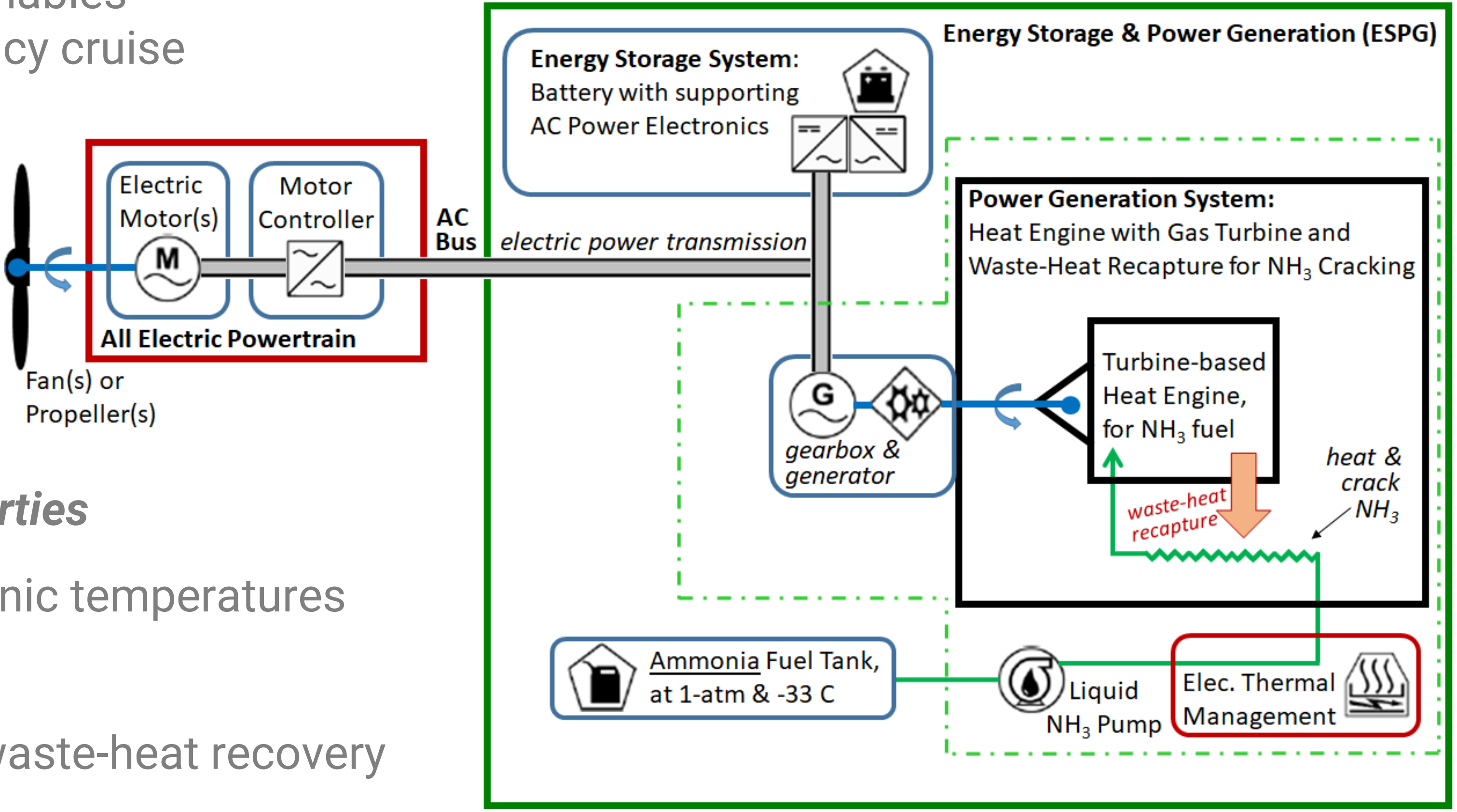
ZAPturbo – Phase 1 Overview

Fed. funding:	$2.7M
Length	24 mo.

Context: *Sustainability* – seek zero in-flight carbon deposition, at commercial scale

History & Synergy: Hybrid-Electric Architecture for High Efficiency

- Synergy: Hybrid-Electric architecture enables NH_3 plant optimization for high-efficiency cruise
- History: Builds on RTX/RTRC Electrified Aircraft Propulsion (EAP) investment & research



CNLF: Recognize Ammonia's Unique Properties

- Liquid "hydrogen carrier" at **non**-cryogenic temperatures
- $2\ NH_3 \rightarrow N_2 + 3\ H_2$
- High thermal absorption capacity, for waste-heat recovery

…..basis for efficient system……

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ZAPturbo – Team

Team member	Location	Role in project
Raytheon Technologies Research Center (RTRC)	East Hartford, CT	Project lead (prime). Ammonia cracking and powerplant component/system development.
Pratt & Whitney	East Hartford, CT	ESPG system modeling & analysis: aircraft mission analysis; gas turbine performance & integration, flowpath, & sizing.
Gas Technology Institute	Des Plaines, IL	Ammonia handling & safety, storage, economics, TT&O.

Raytheon Technologies Research Center

Lance Smith (PI)
Combustion & Fuels

Peter Cocks (co-PI)
Propulsion Team Lead

Sean Emerson
Catalysis & Chem Eng. Team Lead

Brian Holley
Aerodynamics & Turbine Performance

Ulf Jonsson
Rotating & Fluid / NH_3 Machinery

Brent Staubach – Advanced Concepts & Technology Group Leader: Oversight of PW system modeling, cycle analysis, & integration

Jill Klinowski – Technical Coordinator for Technology Programs: Flight mission & engine-system analysis; engine integration studies

Howard Meyer
Gas Processing & Separations, NH_3 Infrastructure, ARPAe/T2M experience

Ronald Stanis
Gas Conversion Tech., TT&O, Ammonia Energy Assoc. Representative

Travis Pyrzynski
NH_3 Experience & Process Safety Management, Lab Procedures & Protocols

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ZAPturbo – Innovation: Additional Detail

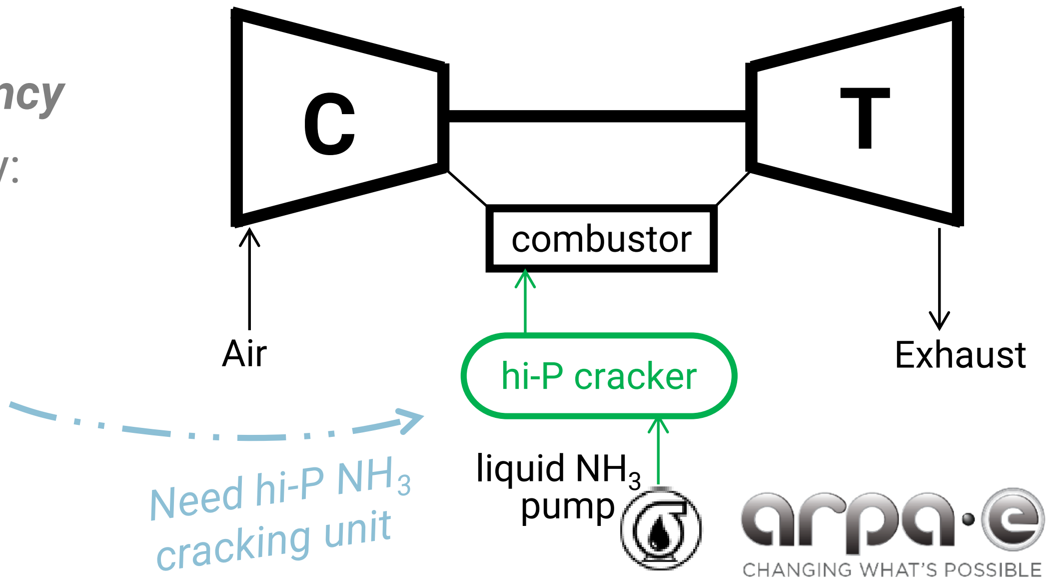
Hybrid-Electric Architecture for High Efficiency

- Cruise-optimized:
  - NH_3 cracking unit: size/weight optimized for cruise power & flows
  - Gas turbine: high-OPR, high-TRIT operation for efficiency @ cruise
  - Gas turbine thrust lapse enables climb power capability: same "reduced" conditions at cruise & climb
- Battery-boost for takeoff power only (recharged during cruise)
- Efficient AC-AC powertrain at turboelectric cruise

	Takeoff	Climbout	Climb	Hold	Cruise	Descend
Time (hours)	0.0833	0.1667	0.25	0.333	5.00	0.50
ESPG Power (% of 26-MW peak)	100%	70%	50%	35%	35%	30%
Power from fuel (% of peak)	70%	70%	50%	35%	35.50%	30%
Power from battery (% of peak)	30%	0%	0%	0%	-0.50%	0%

Use Ammonia's Thermal Absorption Capacity for High Efficiency

- NH_3 thermal absorption capacity, for waste-heat recovery:
  - High heat of vaporization & high heat capacity
  - No NH_3 temperature limit – coke-free heating
  - Endothermic cracking (coke-free)
- $2\ NH_3 \rightarrow N_2 + 3\ H_2$ …… $\Delta H = 2.7$ MJ/kg-NH_3 (15% gain)
- Hot fuel & NH_3 products provide further gains (5 – 10%)



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ZAPturbo – Ammonia's Unique Properties (Very Useful)

- Non-cryogenic hydrogen carrier
  - Store at -33 C (cruise temp.)
- Significant heat absorption capacity of NH_3 resulting from:
  - ✓ NH_3 thermal properties;
  - ✓ coke-free heating;
  - ✓ endothermic cracking;

Endothermic Cracking:

$2\ NH_3 \rightarrow N_2 + 3\ H_2$ … $\Delta H = 2.7$ MJ/kg-NH_3

Table 3: Summary of Properties for Fuels in Liquid Form

Fuel Property	Jet-A (ambient liquid)	H_2 (–253 °C liquid)	NH_3 - anhydrous (–33 °C liquid)
Specific Energy (MJ/kg)	43 MJ/kg	120 MJ/kg	18.6 MJ/kg
Energy Density (MJ/L)	34 MJ/L	8.5 MJ/L	12.7 MJ/L
T_saturation @ 1-atm (°C)	175 - 250 °C	–253 °C	–33 °C
T_saturation @ 10-atm (°C)	325 - 350 °C	–242 °C	+25 °C
T_critical (°C)	375 - 400 °C	–240 °C	+132 °C
P_critical (bar)	19 - 24 bar	12.9 bar	113 bar
Conductivity, k (W/m-K)	0.1 W/m-K	0.1 W/m-K	0.6 W/m-K
Heat Capacity, Cp (kJ/kg-K)	2.0 kJ/kg-K	9.7 kJ/kg-K	4.5 kJ/kg-K
Heat of Vaporization, h_fg (kJ/kg)	350 kJ/kg	446 kJ/kg	1370 kJ/kg
Heat of Cracking reaction (kJ/kg)	achievable? (coke)	N/A	2700 kJ/kg

Compare heat-absorption potential of NH_3 to JP-8 fuel: 5 – 10X +

Cooling Method	JP-8	Ammonia (NH3)
Heat fuel (liquid): 25°C – 125°C *(electronics, oil…)*	220	450
Evaporate liquid fuel @ 125°C	--	500
Heat fuel** (vapor or liquid): 125°C – 525°C	--	1000 - 1500
Endothermic** cracking of fuel (partial or full)	--	up to 2500
***Coke-free for NH3 only (w/out e.g. de-oxygen.)*	**Cooling Capacity (kJ/kg)**	

ZAPturbo – Risks and Challenges

Identifying primary risks to project's success.

#	Risk	Impact	Potential Mitigation Steps
1 (Ph-1)	Ammonia safety, handling, and/or material compatibility concerns	Lab restrictions or delays; Slow technology adoption	- Proactively address protocols & practices - Explore alternative insertion platforms (freight)
2 (Ph-1)	Unsatisfactory NH_3 cracking catalyst performance	Lessened fuel efficiency; Combustion stability	- Explore cycle alternatives to help (P ↓ ; T ↑) - Seek alternate catalysts & promoters
3 (Ph-1)	Plant integration: component mismatch across mission (lapse)	Cracker performance shift; Combustion stability / NOx	- Shift heat sources or cracker conditions - Evaluate combustor robustness & designs
4 (Ph-2)	Plant integration: control of transients, startup/shutdown	Need for ground support or complex workarounds	- Capitalize on hybrid-electric system availability - Adopt learning from combined-cycle plants
5 (Ph-2)	Ammonia combustion: NOx emissions due to fuel-bound N-atoms	Regulatory concerns; Slow technology adoption	- Obtain/develop/evaluate NH_3 models for NOx - Acquire sub-scale gas-turbine combustor data
6 (Ph-2)	Ammonia combustion: stability & anchoring – unknown @ GT conditions	Non-optimal combustor design (large, high-NOx, …)	- Obtain/develop/eval. NH_3 combustion models - Acquire sub-scale gas-turbine combustor data

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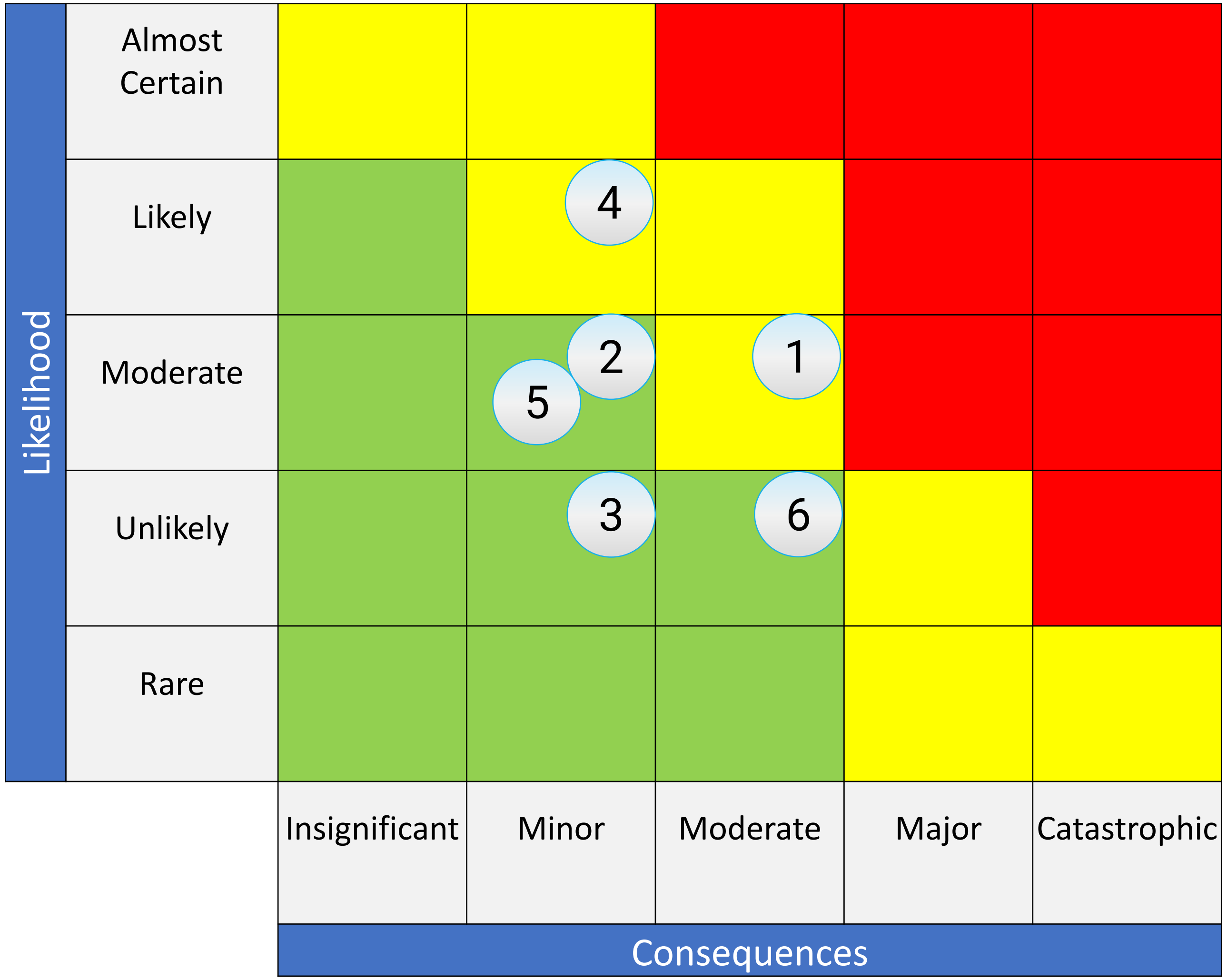
ZAPturbo – Initial Risk Assessment



X Start of project

Risk	#
Ammonia safety, handling, and/or material compatibility concerns	1 (Ph-1)
Unsatisfactory NH_3 cracking catalyst performance	2 (Ph-1)
Plant integration: component mismatch across mission (lapse)	3 (Ph-1)
Plant integration: control of transients, startup/shutdown	4 (Ph-2)
Ammonia combustion: NOx emissions due to fuel-bound N	5 (Ph-2)
Ammonia combustion: stability & anchoring – unknown @ GT cond.	6 (Ph-2)

ZAPturbo – Task Outline & Technical Objectives

Phase-1: ***Risk Reduction Experiments & Conceptual Propulsion System Design***

- Tasks:
  - System evaluation & integration: component matching & performance requirements for ESPG conceptual design
  - Conceptual/modeling design of low-NOx combustor, for ammonia-based fuel
  - High-pressure experimental evaluation of ammonia cracking catalysts
  - Testing & demonstration of ammonia-handling materials & components, and of laboratory cracking unit at high-P
- Objectives:
  - Define component operating conditions, as needed to achieve target efficiency (66%)
  - Demonstrate high-pressure ammonia cracking unit, with performance sufficient to support 66% efficiency target

Phase-2: ***Sub-Scale Demonstration of ~100-kW Fuel-to-Electricity Conversion***

- Tasks:
  - Bench-scale testing & evaluation of low-NOx combustor design(s), for ammonia-based fuel
  - Design and Fabricate Required Components for ~100-kW Demonstration:
    - Sub-scale high-pressure ammonia cracking unit
    - Sub-scale high-pressure combustor for ammonia-based fuel
    - ~100-kW AC turbogenerator
  - During operation, measure electric power generation, and all energy inflows & outflows: report thermal efficiency
  - Measure NOx concentration in exhaust
- Objective: In sub-scale test, show technical viability of 66% energy conversion efficiency

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ZAPturbo – Technology-to-Market Approach

- *Commercialization plans:*
  - *The ZAPturbo project plans have been communicated to RTX commercial aerospace BUs:*
    - *Pratt & Whitney Aircraft (PWA) – large commercial engines*
    - *Pratt & Whitney Canada (PWC) – regional & business aircraft engines*
    - *Collins Aerospace – aircraft fuel systems*
  - *There is now significant BU and customer interest in sustainable aviation: the ZAPturbo team will continue to report progress to RTX BUs, and engage with them regarding future markets & opportunities.*
  - *GTI is actively engaged in the ammonia energy community, including the Ammonia Energy Association, and will facilitate new customer interactions with the team.*

- *Anticipated first markets:*
  - *Business aircraft may be a first entry point, based on customer interest & potential investment.*

- *Anticipated long-term markets:*
  - *Commercial aviation will provide the largest impact.*

- *Timeline TBD.*

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Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)

REEACH

Phase 1 Program Kickoff Meeting
January 26, 27, 28, 2021 – WebEx